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Research Article

Assessing Mechanical Properties of Hot Mix Asphalt with Wire Wool Fibers

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This paper investigates the potential application of wire wool in the modification of hot asphalt mixes (HMA). Wire wool material is widely available at local markets as a by-product of wire wool industry and as waste products from homes. For the purpose of this study, wire wool was cut into small pieces so that it can be placed in the asphalt mixes. Different percentages of wire wool were incorporated with the hot asphalt mixes (0.0%, 0.25%, and 0.5%) of the total weight of the asphalt binder. Various experimental tests were used to evaluate the modification effectiveness of combining wire wool with hot asphalt mixes, namely, the Marshall Stability, indirect tensile strength (ITS), dynamic creep, fatigue, and rutting tests. Test results proved that the addition of wire wool increased the tensile strength of the asphalt concrete mixes. However, rutting increased due to increasing percentage of wire wool. Therefore, mixes containing wire wool can be used in areas where rutting is not the expected predominant distress type.

1. Introduction

Asphalt concrete mixes have attracted many researchers and engineers trying to improve their dynamic properties due to the growth in traffic volume, traffic loading and tire pressure, and harsh environments which have ultimately increased stresses on asphalt pavements [1–4].

Huge traffic loading and harsh environments were two key parameters that affect mechanical and dynamic properties of HMA pavement. Early signs of cracks and deterioration were shown on the pavement as major consequences of these parameters. Commonly, local pavement temperatures range between −7°C during winter season and up to 48°C during summer time. In addition, temporal temperature fluctuations (daily and seasonally) and the rapid increase in traffic volume and loading have put more stress on HMA pavement. Therefore, there is a great need to modify and improve HMA mixes to diminish stress cracking and permanent deformation which occur at low and high temperature ranges, respectively.

Modifications of the asphalt binders were the main approaches taken to improve the performance of asphalt pavement. Many researchers have performed investigations to improve and upgrade properties of HMA mixes [5]. On the contrary, other researchers have studied improving properties of HMA mixes by utilizing recycled additives such as fibers and polymers. A rigorous literature review showed that the increase in the interests of researchers in the field of HMA mixes enhancement was due to many reasons, such as (a) pavement distresses and early cracks which resulted from growing traffic volumes, loads, and tire pressure, (b) economic aspects associated with rehabilitation and replacement of deteriorated pavement specially oil refineries' policy in favor of producing light fuels instead of asphalt, (c) new trend towards constructing roads with thin pavement thickness and differed maintenance procedures, (d) availability of by-product waste materials which encourages researchers and environmentalists to utilize them in various environmental friendly ways to reduce their hazards, and (e) persistent temperature fluctuations which lead to distressing pavement and produce permanent deformations [3].

The prominences of researchers are to a safe disregard of the by-product wastes by incorporating them as HMA additives to improve dynamic and mechanical pavement or binders' properties [6]. It is well illustrated in the literature that using the additives of such wastes in the HMA binders has improved many properties such as repair and remediation against distresses resulting from structural or surface defects and thermal fatigue cracking.

Many researchers [2, 6–9] recommended that modified HMA binders should meet the following criteria: (a) dynamic properties improved at high temperature values to achieve better resistance to structural defects such as rutting and shoving; (b) at low temperatures, binders should achieve lower stiffness value to resist thermal fatigue and cracking; (c) binders with low stiffness value at high temperatures would facilitate the workability (pumping, mixing, and compaction) process of HMA mixes; and (d) stripping resistance increases by improving adhesion properties between HMA mixes' constituents (aggregate and binder).

Previous studies on the effects of additives on the behavior of HMA [2, 10–12] illustrated that the use of fiber waste materials has positively enhanced asphalt pavement properties such as Marshall Stability, crack resistance, tensile strength, and resistance to permanent deformation. Moreover, it increases pavement service life, decreases maintenance costs, and ultimately helps in creating a new valuable market to manage waste fibers.

This study introduced a new fiber waste material that has never been combined with asphalt mixes. Wire wool is the name given to fine metal wire that are bundled together to form a cluster of abrasive, sharp-edged metal strips. The metal strips are massed together in a sheet, folded, and turned into pads that are easily held in the hand. These wire wool pads are used for a variety of purposes, but primarily used for their ability to clean and cut through grease and grime. This investigation was conducted to assess mechanical and dynamic properties of HMA binder with wire wool. The modification efficiency is evaluated by the improvement in the performance of prepared asphalt hot mixes. This study was conducted to assess the performance of wire wool modified HMA mixes through standard laboratories procedures and to determine the optimum percentage of the wire wool and asphalt content that should be added.

Wire wool as a by-product of steel manufacturing is known to possess some reinforcing characteristics. This research indicated that wire wool decreases the cracks by increasing the tensile strength of the HMA, in spite of the fact that wire wool increases the required optimum asphalt content because of the increased surface area.

2. Experimental Program

A schematic diagram of the experimental program conducted in this study is shown in Figure 1. The experiment was divided into four phases. Phase I involved collection and characterization of aggregate and asphalt and preparing of wire wool with the required size. Asphalt samples were collected from a local asphalt cement-producing refinery.

Table 1 shows the physical properties of the used asphalt cement mixes. Properties were evaluated in accordance with AASHTO specifications for 60/70 penetration asphalt. The aggregate used in this study was crushed limestone and its gradation was in accordance with the local authority standards in charge of road construction and maintenance

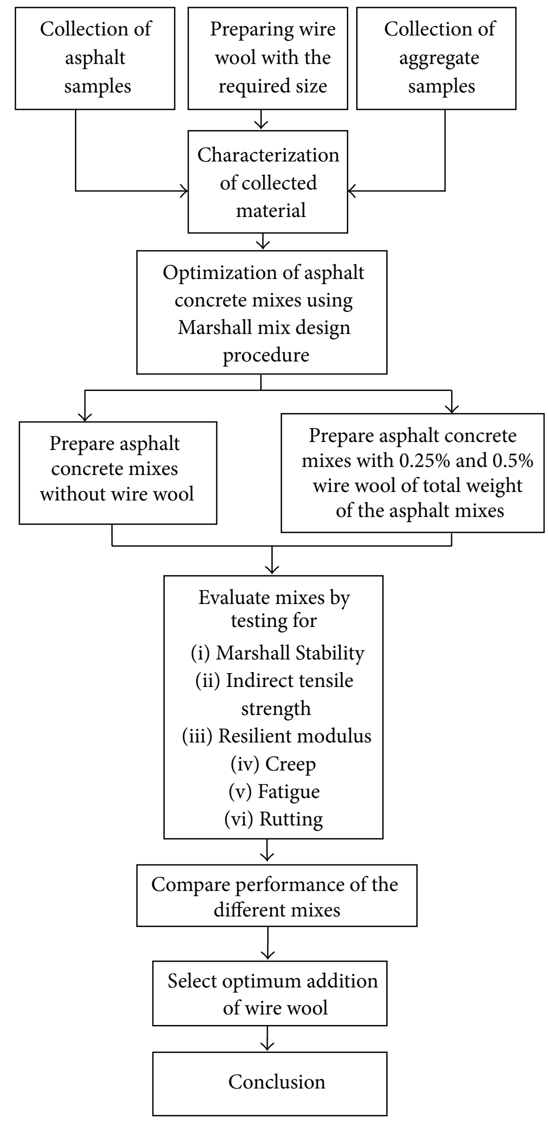

Figure 1: Flow chart of the experimental program.

(Figure 2). The public authority suggested the use of gradation designed for heavy traffic wearing course. The wire wool utilized here can withstand up to 170°C. It was cut into small pieces of length equal to the maximum size of aggregate (3/4 inches) so that it can be placed in the asphalt mixes. The analysis of the wire wool used in this experiment is presented in Table 2.

Phase II involved employing the design procedure for mix (ASTM D1559) set by public authority. Optimum asphalt content (OAC) was evaluated using 4-in samples. Mix samples were incorporated with three wire wool percentages (0%, 0.25%, and 0.5%) and the air void ratio was set to 4%. Results showed that the corresponding OAC values were 5.13%, 5.41%, and 5.69% (weight basis), respectively. The increase in the OAC with the increase of wire wall content is due to the increase of aggregate and additive surface area.

For each calculated optimum asphalt content, properties of HMA mixes such as Marshall Stability, air voids, void ratio in aggregates, and voids filled with binder were examined to

Table 1: Physical properties of the used asphalt cement.

Property	Value	AASHTO specifications for 60/70 penetration asphalt	
		Minimum	Maximum
Penetration (0.1 mm)	66	60	70
Flash point (°C)	320	232	—
Ductility at 25°C (cm)	134	100	—
Specific gravity at 25°C	1.032	1.01	1.06
Softening point (°C)	53	48	56
Penetration of residue (% of original)	66	54	—
Weight loss on heating (%)	0.58		0.8

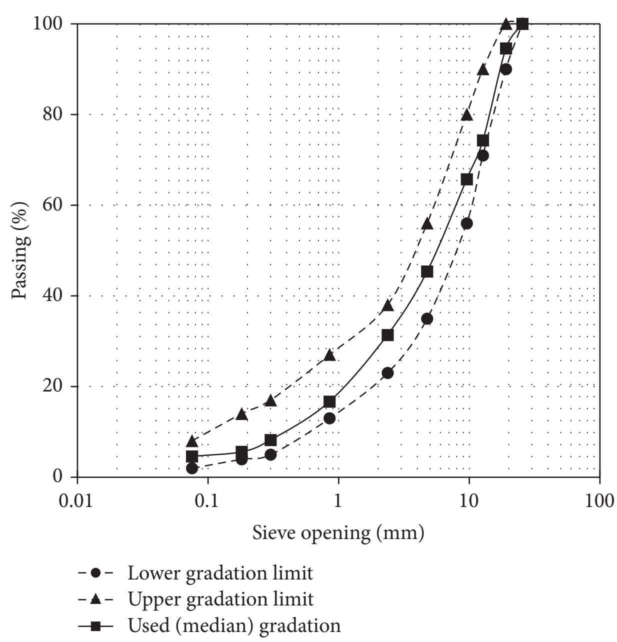

Figure 2: Ministry of Public Works and Housing specified gradation limits and used gradation.

validate that their ranges are within specifications set by the local governmental authority for heavy traffic load wearing course. For this purpose, 36 HMA samples with various wire wool mix percentages were prepared.

Phase III involved evaluation of the effectiveness of additives by looking at the improvements in the Marshall Stability, indirect tensile strength (ITS), rutting, fatigue, and creep of the prepared samples.

Phase IV focused on selecting the optimum percentage of wire wool content.

3. Results and Discussion

Classification experiments according to AASHTO M 20 specifications were conducted on the used asphalt cement. Table 1 shows the results of the performed experiments. Results revealed that the used asphalt can be classified as grade 60/70 penetration asphalt. Several types of wire wool were evaluated to choose the type that can withstand high temperatures and can be mixed properly to minimize the formation of lumps in the asphalt mix. Properties of the selected wire wool are shown in Table 2.

Table 2: Physical analysis of the used wire wool.

Property	Value
Material	Stainless steel
Color	Gray
Length	3/4 inches (maximum size of aggregate)
Thickness	0.0046 mm
Width	0.438 mm

3.1. Marshall Stability Test Results (ASTM D1559). In this test, experimental procedures in accordance with ASTM D1559 were performed. For each wire wool mixing ratio, 6 samples of HMA mixes were prepared and immersed in a water bath at 60°C. Then three samples were tested for Marshall Stability after 30 minutes of immersion while the remaining three samples were tested after 24 hours. Results are shown in Table 3.

Marshall Stability test results proved that samples with 0% wire wool mixing ratio and 30 min immersion duration have the highest Marshall Stability value, followed by the 0.25% and 0.5% wire wool. However, what can be noticed from the obtained results is that the difference between the obtained values was not remarkably high. Therefore, it can be concluded that stability may not be considered as a realistic choice as a discriminating test.

Table 3 also shows that the average loss in Marshall Stability decreased when the wire wool percentage increased in the mix. The value of average loss in Marshall Stability after adding wire wool at 0.5% decreased by 16.65% compared to the control mix, and for the 0.25% wire wool it decreased by 7.72% compared to the control mix. This might be related to the extra added amount of asphalt cement due to the addition of the wire wool.

3.2. Water Sensitivity Test (ASTM D 4867-09). The experimental procedures were conducted in accordance with ASTM D 4867-09 test procedure. Water sensitivity test was performed to investigate the effects of wire wool addition on striping resistance (water susceptibility) of the HMA mixes by measuring the loss in the indirect tensile strength (ITS) after 24 hours of immersion in a water bath at 60°C. The obtained results, shown in Table 4, indicate that increasing the wire wool mixing ratio would reduce the average loss in the value of tensile strength because of water damage. Samples with 0.5% addition of wire wool have the highest improved ITS loss value of 15.9%. Therefore, addition of wire wool has reduced the loss of indirect tensile strength (ITS) which can be mainly attributed to the increase in the amount of asphalt content and presence of wire wool wires.

Table 3: Effect of wire wool addition on Marshall Stability.

% wire wool	Marshall Stability after 30 min immersion (KN)			Marshall Stability after 24 h immersion (KN)			Average loss in Marshall Stability (%)
	Sample number	Stability	Average	Sample number	Stability	Average	
0%	1	11.2	11.93	10	9.8	9.83	17.60%
	2	15.1		11	9.7		
	3	9.5		12	10.0		
0.25%	4	10.0	9.47	13	21.0	16.90	10.18%
	5	10.5		14	16.5		
	6	7.9		15	13.2		
0.5%	7	7.5	8.00	16	7.1	7.90	1.25%
	8	7.5		17	8.2		
	9	9.0		18	8.4		

Table 4: Effect of wire wool addition on the indirect tensile strength (ITS).

% wire wool	ITS—nonconditioned (KPa)			ITS—after conditioning (KPa)			Average loss in ITS (%)
	Sample number	ITS value	Average	Sample number	ITS value	Average	
0.0%	1	1171.9	1143.4	10	722.3	866.0	24.3
	2	1141.9		11	877.0		
	3	1116.4		12	998.9		
0.25%	4	1088.8	1047.2	13	785.9	841.3	19.7
	5	991.7		14	844.9		
	6	1061.1		15	893.2		
0.50%	7	1035.7	1005.7	16	827.9	846.1	15.9
	8	975.8		17	923.0		
	9	1005.7		18	787.5		

3.3. Dynamic Creep Test. This test was performed by applying a repeated pulsed uniaxial stress on HMA specimens. Linear variable differential transducers (LVDTs) were installed to measure resulting deformations along the same loading direction [13–15]. The applied pulsed uniaxial stress was a feedback haversine pulse type. The pulsed stress used was 207 kPa, and the contact stress was 9 kPa. These values were chosen not to allow the vertical loading shaft to lift off the test specimen during rest period. The duration of pulse width was 100 ms, and 900 ms was the time gap before the application of the next pulse. The test was performed at 25°C. Two thermocouples were used to measure specimen's skin and core temperatures during the test. These thermocouples were located inside the dummy specimen and near the specimen during testing.

The experimental procedures were continued till the value of maximum axial strain limit reached 10,000 microstrains, or 10,000 cycles, whichever occurred first. For the purpose of measuring dynamic properties, three samples of 100 × 70 mm with 4% air void ratio (from each wire wool percentage) were tested and all dynamic properties, such as resilient modulus, creep stiffness, accumulated permanent and resilient strains at failure, and permanent and resilient deformations, were measured and reported in Table 5.

Results for the correlation between axial accumulated permanent deformation and number of cycles are shown in Figure 3 for the various tested groups (i.e., 0.0%, 0.25%, and 0.5% wire wool). Samples with 0.5% wire wool mix ratio showed the best results over other HMA mix ratios, followed by 0.0% and 0.25% wire wool, respectively. This can be explained based on the nature of the wire wool bonding and fiber properties, which ultimately improved creep resistance of the HMA mixes. On the contrary, samples with 0.25% wire wool mixing ratio have decreased the quantity of improvement of the creep resistance compared to the control mix, because, during testing, it was noticed that lumps of wire wool are formed in the samples due to improper mixing, so wire wool was not distributed evenly in the sample.

Table 5: Effect of adding wire wool on the creep properties of the mix.

Property	Wire wool percentage		
	0.0%	0.25%	0.50%
Core temperature (°C)	23.38	23.68	24.05
Contact stress (KPa)	9	9	9
Deviator stress (KPa)	207	207	207
Dynamic load (KN)	1.641	1.506	1.594
Permanent deformation (mm)	0.445	0.844	0.151
Resilience deformation (mm)	0.031	0.0354	0.044
Accumulated strain (%)	0.445	0.844	0.151
Resilient strain (%)	0.031	0.036	0.044
Resilient modulus (MPa)	1051.99	559.183	465.708
Creep modulus (MPa)	41.68	23.665	135.411

3.4. Fatigue Performance. All HMA specimens with different wire wool mixing ratios were tested diametrically by applying

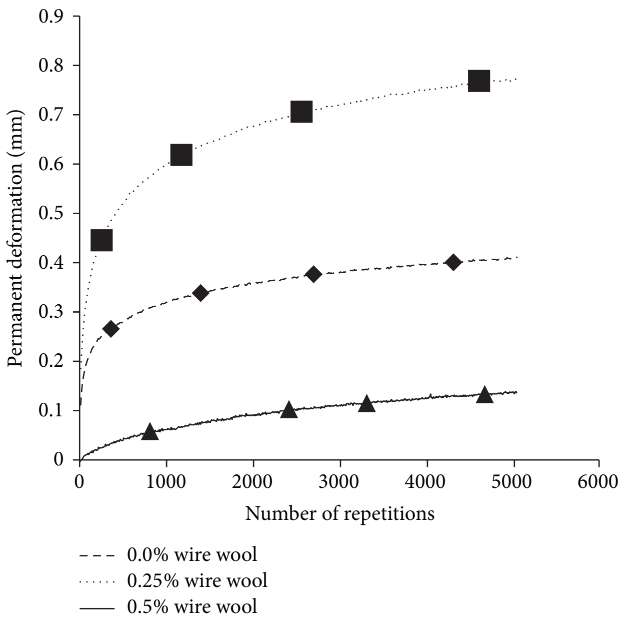

Figure 3: Creep behavior results for different HMA mixes.

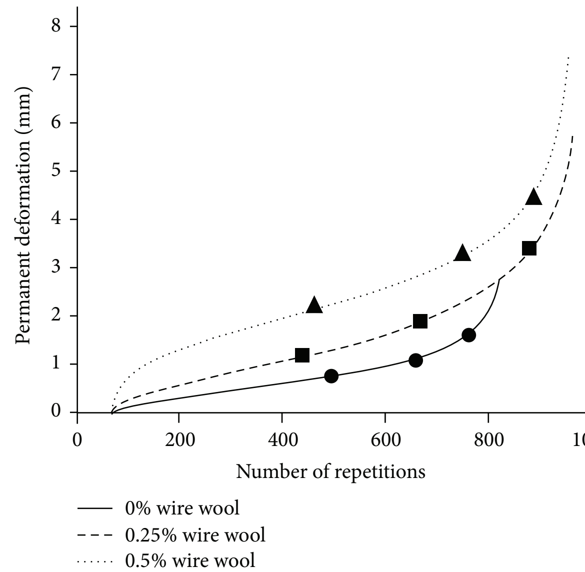

Figure 5: Permanent deformation behavior results for different HMA mixes.

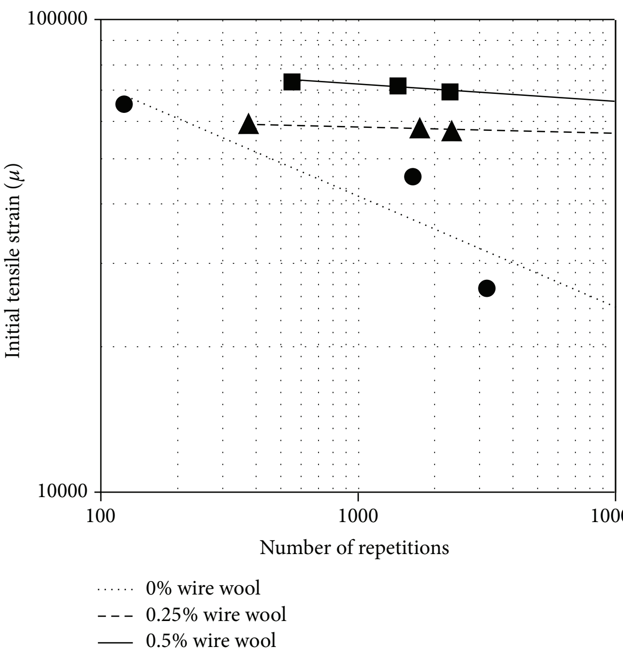

Figure 4: Fatigue behavior results for different HMA mixes.

repeated pulsed uniaxial loading to measure loading cycle numbers required at failure. Nine specimens were fabricated and various initial tensile strain levels (at least three levels) were set during the experiments to obtain a wider range of failure cycle. Figure 4 shows the obtained results with regression lines denote the mean of specimens at each strain level. A normal linear relationship was depicted between the ITS and number of applied load repetitions (fatigue life cycle) on logarithmic scale.

Fatigue test results showed that HMA specimens with 0.5% wire wool mixes have significantly improved the level of the fatigue life, followed by percentage of 0.25% and 0% wire wool. Thus, wire wool fibers have improved fatigue life of HMA mixes substantially due to its bonding properties.

3.5. Permanent Deformation. This test was performed using two vertical LVDTs. Vertical permanent deformation was concurrently recorded while fatigue experiment was running. Test results for the permanent deformation experiment are shown in Figure 5. Analysis proved that HMA samples passed through three distinguished stages, namely, densification, steady state, and failure.

Figure 5 shows a comparison of different mixes samples performance under permanent deformation test. Control mix with 0% wire wool got the best performance, followed by the 0.25% and 0.5% wire wool. This can be explained based on the fact that increasing wire wool increased required asphalt content that decreased the air voids leading to increase in rutting potential.

4. Conclusions

This study presented a comparative study between the currently used hot asphalt mixes and those mixes with an addition of wire wool at different percentages. Measurements of the loss of the Marshall Stability, water sensitivity, dynamic creep, rutting, and fatigue tests were conducted, compared, and analyzed. Based on the performed tests, the following conclusions can be drawn:

(1) The mix containing wire wool showed less reduction in both loss in Marshall Stability and loss in indirect tensile strength (ITS) compared to the control mix. This improvement was proportional to the added wire wool percentage.

(2) The study revealed that mixtures containing wire wool may have longer fatigue life than the control mix.

(3) Rutting increased due to increasing percentage of wire wool. Therefore, mixes containing wire wool can be used in areas where rutting is not the expected predominant distress type.

The current study had shown that wire wool has some advantages as an additive to HMA. At the same time, wire wool also has few disadvantages that need to be kept in mind. One drawback is that wire wool is prone to disintegration when heated along with the HMA. The other drawback is that wire wool, as being metallic in nature, is vulnerable to rust when exposed to moisture.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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